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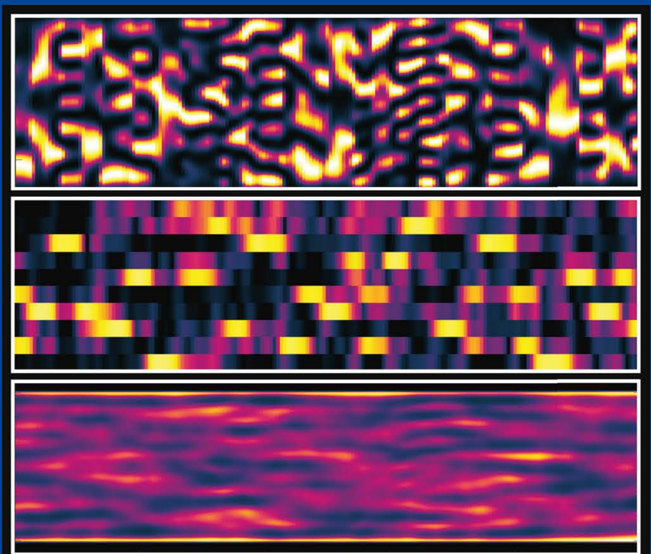
Analysis of Spatio-Temporal Phenomena in High-Brightness Diode Lasers using Numerical Simulations



Anissa Zeghuzi

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aus der Reihe:

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Analysis of Spatio-Temporal Phenomena in High-Brightness Diode Lasers using Numerical Simulations

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Innovations with Microwaves and Light

Research Reports from the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik

Preface of the Editors

Research-based ideas, developments, and concepts are the basis of scientific progress and competitiveness, expanding human knowledge and being expressed technologically as inventions. The resulting innovative products and services eventually find their way into public life.

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High-power broad-area diode lasers are key components of various state-of-the-art laser systems. Accordingly, a strong research focus is on improving output power and beam quality (i.e. brightness). In this thesis, optical, electronic and thermal models are presented which allow a numerical simulation of the complicated spatio-temporal behavior of these lasers. The simulation tool developed is used to elucidate the root causes limiting laser brightness and to suggest new cavity designs improving the beam quality.

We wish you an informative and inspiring reading

Prof. Dr. Günther Tränkle
Director

Prof. Dr.-Ing. Wolfgang Heinrich
Deputy Director

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Abstract

Broad-area lasers are edge-emitting semiconductor lasers with a wide lateral emission aperture, that enables high output powers, but also diminishes the lateral beam quality and results in their inherently non-stationary behavior. Research in the area is driven by application and the main objective is to increase the brightness, that includes both the output power and lateral beam quality. To understand the underlying spatio-temporal phenomena and to apply this knowledge in order to reduce costs for brightness optimization, a self-consistent simulation tool taking into account all essential processes is vital.

Firstly, in this work a quasi-three-dimensional opto-electronic and thermal model is presented, that describes well essential qualitative characteristics of real devices. Time-dependent traveling-wave equations are utilized to describe the inherently non-stationary optical fields, which are coupled to dynamic rate equations for the excess carriers in the active region. This model is extended by an injection current density model to accurately include lateral current spreading and spatial hole burning. Furthermore a temperature model is presented that includes short-time local heating near the active region as well as the formation of a stationary temperature profile. The former is significant for short pulse operation with high injection currents, as the fast-growing thermally induced waveguide can result in a transition from a gain-guided to an index-guided structure. Under continuous-wave operation the latter longitudinally varying stationary temperature profile leads to a near-field shrinkage at the anti-reflection coated facet, resulting in an unfavorable carrier accumulation at the stripe edges and an enhanced power density that lowers the threshold for facet damage.

Secondly, the reasons of brightness degradation, i.e. the origins of power saturation and the spatially modulated field profile are investigated. Under continuous-wave operation power saturation is mainly attributed to device heating, whereas under pulsed operation it is identified to be partly caused by spatial hole burning, lateral current spreading and two-photon absorption. Furthermore, spatio-temporal power variations play a role in the power saturation process and should not be neglected. The multi-peaked field profile of broad-area lasers is sometimes attributed to a modulation instability arising from spatial hole burning. Here, the optical field is considered to spontaneously break-up into small filaments, because the refractive index in areas of high intensity rises, thus creating a local waveguide. However, in this theory changes of the optical gain due to carrier density fluctuations and the non-stationarity of the system are not taken into account, and thus the traveling-wave simulations could not support the theory of filamentation by this indirect Kerr-type non-linearity. An alternative understanding of the transverse instabilities bases on the simultaneous lasing of a large number of lateral waveguide modes. And indeed, a post-processing analysis of the optical field obtained from a traveling-wave simulation, which makes no pre-assumption regarding modes, indicates, that in lasers with a lateral waveguide a clear mode structure is visible which is neither destroyed by the dynamics nor by longitudinal effects.

And lastly, designs that mitigate those effects that limit the lateral brightness under pulsed and continuous-wave operation are discussed. An increased beam quality can be obtained by implantation of the contact layer next to the injection stripe to counteract current spreading or by a lowered p-layer resistivity to reduced spatial hole burning. The narrowed near-field intensity resulting from the longitudinally varying temperature distribution under continuous-wave operation can be counteracted by index-guiding trenches to increase efficiency and the threshold for facet damage. And finally, a novel “chessboard laser” design is presented that utilizes longitudinal-lateral gain-loss modulation and an additional phase tailoring to theoretically provide a single-lobed far field with a full lateral far-field angle of $\Theta_{40\%} = 0.4°$ (40% power content) at an injection current of 100 A under pulsed operation.

Kurzfassung

Breitstreifenlaser haben eine breite Emissionsapertur, die es ermöglicht eine hohe Ausgangsleistung zu erreichen. Gleichzeitig führt sie jedoch zu einer Verringerung der lateralen Strahlqualität und zu ihrem nicht-stationären Verhalten. Forschung in diesem Gebiet ist anwendungsgetrieben und somit ist das Hauptziel eine Erhöhung der Brillanz, die sowohl die Ausgangsleistung als auch die laterale Strahlqualität beinhaltet. Um die zugrunde liegenden raumzeitlichen Phänomene zu verstehen und dieses Wissen zu nutzen, um die Kosten der Brillanzoptimierung zu minimieren, ist ein selbst-konsistentes Simulationstool entscheidend, das alle wichtigen Prozesse beinhaltet.

Zunächst wird in dieser Arbeit ein quasi-dreidimensionales elektro-optisch-thermisches Model präsentiert, das wesentliche qualitative Eigenschaften von realen Bauteilen gut beschreibt. Zeitabhängige Wanderwellen-Gleichungen werden genutzt, um die inhärent nicht-stationären optischen Felder zu beschreiben, welche an eine Ratengleichung für die Überschussladungsträger in der aktiven Zone gekoppelt sind. Das Model wird um eine Injektionsstromdichte erweitert, die laterale Stromspreizung und räumliches Lochbrennen korrekt beschreibt. Des Weiteren wird ein Temperaturmodel präsentiert, das kurzzeitige lokale Aufheizungen in der Nähe der aktiven Zone und die Formierung einer stationären Temperaturverteilung beinhalten. Ersteres ist für Kurzpuls-Anregung mit hohen Stromdichten bedeutend, da der schnell anwachsende thermisch induzierte Wellenleiter zu einem Übergang von einer gewinn- zu einer indexgeführten Struktur führen kann. Bei Dauerstrich-Betrieb führt die letztere longitudinal variierende stationäre Temperaturverteilung zu einer Nahfeldeinschnürung an der antireflektionsbeschichteten Facette und diese wiederum zu einer unerwünschten Ladungsträgerakkumulation am Rande des Injektionsstreifens und zu einer erhöhten Leistungsdichte die zu Facettenschäden führen kann.

Im zweiten Teil werden die Gründe von Brillanzdegradierung, also die Ursprünge der Leistungssättigung und des nicht diffraktionslimitierten Fernfeldes, untersucht. Unter Dauerstrichbetrieb ist Leistungssättigung vorrangig thermisch induziert, wobei bei gepulst betriebenen Dioden als Gründe räumliches Lochbrennen, laterale Stromspreizung und Zwei-Photonen-Absorption identifiziert werden. Des Weiteren wird gezeigt, dass raumzeitliche Leistungsvariationen eine Rolle bei der Leistungssättigung spielen und nicht vernachlässigt werden sollten. Die modulierten Feldprofile von Breitstreifenlasern werden manchmal auf Modulationsinstabilitäten zurückgeführt, die durch räumliches Lochbrennen entstehen. Hier wird angenommen, dass sich das optische Feld spontan in einzelne Filamente aufgliedert, da eine Brechungsindexerhöhung in Bereichen hoher Intensität zu einem lokalen Wellenleiter führt. Da in der beschriebenen Theorie Änderungen des optischen Gewinns durch räumliche Ladungsträgeränderungen und die Dynamik des Systems nicht berücksichtig wurden, können Simulationen auf Basis der Wanderwellen-Gleichung diese Hypothese von Filamentierung nicht bestätigen. Eine alternative Erklärung der transversalen Instabilitäten gründet auf der Annahme der simultanen Anregung einer großen Anzahl lateraler Wellenleitermoden. Eine Analyse des optischen Feldes, simuliert mit dem Wanderwellenmodel, zeigt eine klare Modenstruktur in Lasern mit lateraler Wellenführung, die weder durch die Dynamik noch durch longitudinale Effekte zerstört wird.

Im letzten Teil werden Laserentwürfe besprochen, welche die laterale Brillanz verbessern. Eine erhöhte Strahlqualität kann durch Implantation der Kontaktschicht neben dem Injektionsstreifen zur Verringerung von Stromspreizung oder durch eine Verringerung der Resistivität der p-Schicht zur Eindämmung von räumlichen Lochbrennen erzielt werden. Die verengte Nahfeldintensität, die aus der longitudinalen Variation der Temperaturverteilung bei Dauerstrichbetrieb resultiert, kann durch indexführende Gräben entgegengewirkt werden, um die Effizienz zu erhöhen und Facettenschäden vorzubeugen. Zuletzt wird ein neuartiges "Schachbrettlaser" Design präsentiert, bei dem longitudinal-laterale Gewinn-Verlust-Modulation mit zusätzlicher Phasenanpassung ausgenutzt wird, um ein simuliertes Fernfeld mit einem lateralen Fernfeldwinkel von $\Theta_{40\%} = 0.4°$ bei einem gepulsten Injektionsstrom von 100 A zu erhalten.

Parts of this work have been presented in

Book chapter

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Contents

Chapter 1

Introduction and Background

High-power broad-area lasers

High-power broad-area (BA) lasers are edge-emitting semiconductor lasers with a lateral emission aperture of some tens to hundreds of micrometers which is wide compared to the emitting near infrared wavelength, making them the most efficient tool for conversion of electrical into optical energy. Due to their very high output power, high efficiency, small size and low cost in mass production there is a strong industry demand. Although they are mainly used as pump sources, their fields of application have diversified and they can be for example also employed for direct material processing or light detection and ranging (LiDAR) systems needed for autonomous driving.

For optical gain to arise in semiconductor lasers, population inversion is obtained by electrical pumping. To restrict the carrier flow and to obtain a large carrier density in the active region heterostructures with different band gap materials grown by metalorganic vapour-phase or molecular-beam epitaxy on a crystalline substrate are utilized. The broad-area lasers investigated in this thesis consist of n-doped $Al_xGa_{1-x}As$ confinement and cladding layers with appropriate Al mol fractions x, single InGaAs quantum-well (QW) active regions, p-doped confinement and cladding layers and a highly p-doped GaAs contact layer grown on a GaAs substrate, Fig. 1.1. The epitaxial structure is metalized with a gold contact and soldered p-side down on a CuW submount, Fig. 1.1(d). In high-power lasers large optical cavities are employed with a comparatively weak vertical waveguide to reduce facet load so that high output powers can be achieved even under continuous wave (CW) operation.

BA lasers reach extremely high output powers, but exhibit a complex non-stationary spatio-temporal and highly non-linear behavior as a result of the interaction of optical, electrical and thermal phenomena. Due to the interplay of spatial depletion of carriers by stimulated emission and the insufficiently fast transport of injected carriers into the depleted regions spatial hole burning occurs. On the one hand, the resulting increase of the real part of the refractive index in those regions creates a local waveguide and leads to self-focusing, which is sometimes referred to as "filamentation" [1, 2]. On the other hand, due to high stimulated recombination and reduced amplification, the carrier density and thus the optical gain is decreased in the created waveguide core, which leads to self-defocusing. The result is a highly dynamic optical field, that can be well described in the mode picture: Single mode emission becomes unstable just above threshold because, due to lateral spatial hole burning, any mode saturates the optical gain in those parts of the active layer where the mode intensity is high. The